gases. As the background gets brighter, helium absorption, having little intensity, becomes less and less obvious. Hydrogen absorption, on the contrary, becomes more and more extensive, until it in turn becomes secondary to the absorption due to metallic vapors.

The curves showing the temperature and pressure at which condensation takes place indicate steadily rising pressure, and rising temperature (and, therefore, intrinsic brightness) until the critical point is reached. From this point no further change in $\frac{T}{P}$ can alter the temperature of the photosphere. As it sinks lower and lower the density of absorption increases. If the metallic-line spectrum of the sun may be supposed to be formed under the conditions represented by the curve *S*, on passing to the next cooler line we might have the denser absorption of *Arcturus*.

If the ratio $\frac{T}{P}$ be still smaller we come to the curve *A*. Here the photosphere is still deeper. The outer parts of the superincumbent gases are much cooler, and compound vapors may be formed. If so, we should expect that the absorption should consist of metallic lines, flutings, and general absorption of the kind known as smoke-veil, for instance, *α Orionis* and *Antares*.

Continuing the process, such a spectrum should grow in intensity until the light of the photosphere should be hidden by superincumbent vapors, or even nonluminous clouds formed by condensed metals and compounds. The last glimpse of the incandescent depths should be a dull red glow.

Such, then, seems to be the normal history of a star.

There is, however, a special case.

Suppose $\frac{T}{P}$ is very high, but that its large value is due to extreme heat, and that *P* is itself large.

The result should be a very dense gaseous nucleus which should give a continuous spectrum, and therefore act as a deeper-seated photosphere whose light would be veiled by absorption, in which that due to carbon vapor would be a conspicuous feature; but metallic lines would also be present, and if the absorption were great, or the intrinsic brightness of the continuous spectrum small, some of the strong metallic lines would stand out as bright lines—carbon stars. Such stars should pass through the normal sequence as a result of declining temperature, which may explain the former redness of *Sirius*.

It thus appears that bright line white stars should be associated with nebulæ; that white stars being due to the greatest range of conditions should be most numerous, especially among the smaller stars; that solar stars should be next in order of frequency, and should form a larger proportion of the massive stars; that stars with fluted spectra should be comparatively few in number, and should as a rule be massive. Finally, carbon stars, demanding exceptionally high pressure and temperature, should therefore be rare and vast.

There are several other deductions which may be drawn. First, if a binary is formed by the fission of a single star, and the division is equal, both stars should be white, or both solar, or beyond. If unequal, and differing to a sufficient extent, the smaller would adhere to a Sirian spectrum long after the larger and less cooled had passed into the solar stage or beyond; as, for instance, *β Cygni*.

Second, any determination of the temperature of the photosphere is no guide to the temperature of the star center, neither is the position of the photosphere, as shown by the absorption, much help. It is possible to have a large hot star showing exactly the same spectrum as a much smaller and cooler one. The ratio $\frac{T}{P}$ may be identical.

So far it has been assumed that carbon is the cause of all photospheres. It is, of course, possible that different stars may be differently constituted, and that different elements may play similar parts. But all the evidence of the spectroscope indicates a cosmic distribution of the elements best known to us. Moreover, a moment's thought will show that all that has been said in reference to a carbon photosphere will apply with equal force to any substance whatever. If, then, we can have photospheres formed of some heavier atoms, they should be situated deeper in the mass of the star, and should be overlaid by carbon, which should either form a higher photosphere in turn or should betray its presence by absorption. We ought, then, to have as great a variety of carbon stars as we have of other types. The fact of the rarity of carbon stars is one of the strongest evidences that it is preeminently *the* photospheric element. However this may be, the main conclusions here set forth remain unaffected, because they hold good for any substance which forms a photosphere, granting only the four postulates with which we started, and that this substance behaves like all others whose condensation curves are known.

## THEORY OF THE RAINBOW.[1]

By Prof. W. LeConte Stevens, Washington and Lee University. Dated Lexington, Va., May 25, 1906.

This pamphlet by Doctor Pernter is an attempt to put the complete theory of the rainbow into such form as to involve no application of higher mathematics, especially no application of calculus, and thus to render it suitable for development in the instruction of students who are below the grade of the university or the advanced college class.

To an American teacher, familiar with the limitations found universally in American schools and colleges, the examination of such a paper at once raises the question whether such a demonstration could find a place in any prescribed course in physics in an American college. If not, it would be included in an elective course. This assumption in turn raises the question whether such a subject would probably be attacked voluntarily by any student not already in possession of such elementary knowledge of calculus as to prepare him for the many difficulties that are sure to arise if the study of optics is pursued beyond its elementary stage. Gymnasial instruction in Austria is conducted under conditions somewhat different from those of college instruction in America. The fact that interchange of conditions is not possible, and that Pernter's work would quite surely meet with little appreciation here, does not in any way diminish the merit of what he has done, even if the critical reader is compelled to think that the adaptation to secondary schools is very imperfect on account of the inherent difficulties of the subject.

Pernter begins with the statement that in all schools, high and low, the correct theory of the rainbow is wholly ignored, and that everywhere the "incorrect Descartes's theory of effective rays" (wirksamen Strahlen) is taught, "as if the correct explanation of the rainbow had never been given by Airy". The task which he undertakes is that of presenting the results of Airy's work in a form as simple as the nature of the subject may permit.

At the outset, therefore, it is necessary to dissent from the author's assumption. A geometric theory may be incomplete without being incorrect. From the days of Noah the conditions under which the rainbow appears have been observed and generally known. That light is reflected and refracted at the bounding surface between air and water, was familiar to Ptolemy, but the law of refraction was not discovered until 1621 by Snell. Its correct formulation and publication was subsequently made by Descartes, who died in 1650. Ten

[1] Ein Versuch der richtigen Theorie des Regenbogens Eingang in die Mittelschulen zu verschaffen. Von Dr. J. M. Pernter. Wien, 1898. Selbstverlag.

years before Snell's discovery, Antonio de Dominis showed that one reflection and two refractions of light in drops of rain were sufficient to explain the production of a luminous arc in the sky opposite the sun. Descartes gave exactness to the explanation of Dominis by the application of Snell's law. Descartes's work was correct, and the recognition of his "effective rays" does not in any way contravene the subsequent discoveries of Grimaldi, Newton, Huyghens, Young, and others that are now applied in the discussion of the rainbow. Descartes seems to have thought that refraction produced color instead of separating colors; but it was reserved for Newton, sixteen years after Descartes's death, to discover that each hue has its own index of refraction when white light traverses a given medium. Descartes's geometric theory is true whatever may be the hue or index of refraction, but it was insufficient to account for the supernumerary colored bands or alternations of brightness which may be often seen as accompaniments to the rainbow. Young was the first to propose, in 1804, an explanation of these based on the wave theory. His suggestion was afterward confirmed and extended by the mathematical investigations of Potter and Airy about 1835; but this important supplement to the work of Descartes and Newton was in no sense contradictory. The phenomena of diffraction and interference may coexist with those of refraction; and this, indeed, is at times apparently assumed by Pernter, despite his introductory condemnation of "die unrichtige Descartes'she Theorie."

It is probably correct to say that in most, if not all, of the elementary text-books the explanation of the rainbow is limited to the application of the laws of geometrical optics, with no reference to the modifications necessitated by the wave theory of light. The great majority of students who receive baccalaureate degrees have no knowledge of such modification. The subject of rainbows receives scant attention ordinarily, and in such an admirable modern text-book as Drude's Theory of Optics it is not even mentioned. But in Preston's Theory of Light a good discussion may be found, in which the reader is assumed to possess all the mathematical knowledge that the subject naturally suggests. Professor Hastings, in America, has given an excellent discussion in Hastings and Beach's Physics. The pamphlet by Pernter is noteworthy as an attempt to emphasize the importance of the wave theory. His strenuous arraignment of the schools for teaching what is insufficient, rather than incorrect, is perhaps a pardonable exhibition of zeal which should not be taken too seriously.

The theory of the rainbow is best developed by a succession of approximations, beginning with purely ideal conditions.

### FIRST APPROXIMATION.

Let a sheaf of parallel rays meet a sphere of glass or water. Consider only those impinging at a single angle of incidence, $i$, such as 60°. Let $\mu$ be the mean index of refraction, $\mu'$ that for red, and $\mu''$ that for violet. From Snell's law the angles of refraction, $r$, $r'$, $r''$, are readily calculated, and the mean deviation is $i—r$. At the first point of incidence, $A$ (fig. 1, Plate II), some of the light is reflected externally and some refracted to $B$. Here some is reflected internally, but much more emerges with additional mean deviation, $i—r$. The total mean deviation, $\delta$, is thus

$$\delta=2\ (i-r). \tag{1}$$

For the extreme rays we have

$$\delta'=2\ (i-r') \text{ for red;}$$
$$\delta''=2\ (i-r'') \text{ for violet.}$$

Hence a screen properly placed would receive a circular spectral band of width $\delta''-\delta'$. If the globe be of glass, and $i$=60°, as shown, the mean angular diameter, $2\,\delta$, for the circular bow would be about 100°.

This is easily projected experimentally by restricting the light to a suitable angle of incidence on a glass sphere, or by using a glass cone of proper angle, with its vertex toward the source of light. The bow thus produced is the most brilliant possible.

### SECOND APPROXIMATION.

A bow of the kind just described, though always produced, would not be perceptible in the sky, because the refracting sphere and the sun are too nearly in the same direction from the receiving eye. For a visible bow we must consider the rays emergent after one or more internal reflections.

On reaching the reflecting surface $B$, (fig. 2, Plate II), the change of direction by reflection is obviously $\pi-2\,r$. For each one of $n$ internal reflections the total deviation of the mean ray is thus

$$D=2(i-r)+n(\pi-2\,r). \tag{2}$$

For a single internal reflection the emergent mean ray would be received by an eye at $O$ at an angular distance $\pi-D$ from the original direction, and to such an eye all drops of water at this angular distance would appear of the same hue. Assuming $i=60°$ the angular distances for the extreme rays are thus readily calculated and found to be about 42° for red and 40° for violet. A spectral bow, with angular width of 2°, would hence appear in the eastern sky upon a cloud, if the afternoon sun is not obscured. The arch would be lined with red on its outer border and violet on the lower side.

For two internal reflections a similar applications of equation 2 may be made with $n=2$. The result is that a second, but fainter bow may be produced, with angular width of about 3°, the angular distances for the extreme rays being about 51° and 54°, with red on the lower side and violet on the outer border.

For more than two internal reflections the emergent light is so reduced in brightness, or is so directed, as to be almost if not quite imperceptible Often only the primary bow is seen. One or both bows may be seen as complete circles in the spray of a fountain or cascade under favorable conditions.

### THIRD APPROXIMATION.

Thus far we have assumed but a single value, 60°, for the angle of incidence on a drop while in reality this takes all values from zero to 90°. For nearly perpendicular incidence the proportion of light reflected is very small, and the value of $D$ for a single internal reflection is then given by equation 2 as nearly 180°. For nearly grazing incidence the proportion externally reflected is large, hence very little is returned by internal reflection; and the value of $D$ for a single internal reflection, when $i=85°$, is given by equation 2 for red light as 156° 36′. Under the same condition for $i=60°$ the equation gives $D=137°\ 56'$. This is less than either of the preceding values, while the proportion of light refracted and internally reflected is much greater. The internally reflected rays are thus crowded about some mean ray that gives a minimum value of $D$, and these are Descartes's "effective rays". A simple application of calculus to equation 2 makes it possible to find the value of $i$ corresponding to this minimum value of $D$, and thus to compute $D$. For red light it is $i=59°\ 24'$, and $D=137°\ 54'$, which is the supplement of 42° 6′ the angular distance of the red border of the primary bow from the axial line passing through the observer's eye from the sun. Since most of the emergent light corresponds approximately to this angle, but is not confined to this value of $i$, it follows that the entire area within the primary rainbow will receive some light, but none will be deviated beyond the outer margin of the red.

Similar reasoning may be applied to the secondary bow with the result that the region exterior to it will be slightly illuminated while that on its concave side receives none of its scattering rays. The area between the primary and secondary bows is hence that of minimum illumination while the adjacent primary bow is that of maximum illumination. The two bows are separated by a distinctly dark band.

The experimental test of what has just been set forth may be readily made with a spectrometer. At the center is erected a small glass cylinder, this substitute for a sphere being selected because the measurements are restricted to a horizontal plane. The index of refraction being known and the angle of incidence being controllable, the deviations for the different hues are calculated by use of equation 2. A beam of white light is transmitted through a narrow vertical slit and made parallel by the collimator. By suitable shifting of the observing telescope the values of $D$ found by experiment are compared with the indications of theory. If any errors or additional phenomena are discovered the investigation of these is naturally suggested.

To avoid the use of calculus Pernter makes out a table of values of $D$ for selected values of $i$ from 30° to 85°. The results are expressed graphically and the lowest point of the curve is thus found to correspond to an angle of incidence a trifle less than 60°. For greater exactness the following trigonometric method is then given for finding the angle of incidence corresponding to minimum deviation.

By a simple transformation equation 2 becomes

$$D = n\pi + 2\Big(i - (n+1)r\Big).$$

For brevity let $p = n + 1$. Then

$$D = n\pi + 2(i - pr). \qquad (3)$$

This indicates that small alterations of $i$ will produce diminishing alterations of $D$ until the minimum value of $D$ is reached. Let $\alpha$ denote an increment of $i$; let $\beta$ be the corresponding increment for $r$, and $d$ that of $D$. Then

$$D + d = n\pi + 2\Big((i+\alpha) - p(r+\beta)\Big)$$

$$= n\pi + 2(i - pr) + 2(\alpha - p\beta). \qquad (4)$$

Subtracting (3) from (4),

$$d = 2(\alpha - p\beta).$$

The condition that makes $d$ vanish is obviously

$$\alpha = p\beta. \qquad (5)$$

If $I$ denotes the angle of incidence when $d$ vanishes, and $R$ that of refraction, the index of refraction being $\mu$, Snell's law gives

$$\sin(I + \alpha) = \mu \sin(R + \beta).$$

Expanding and reducing this equation, noting that $\alpha$ and $\beta$ are small so that $\sin\alpha = \alpha$, $\sin\beta = \beta$, and $\cos\alpha = \cos\beta = 1$, also that $\alpha = p\beta$, we readily obtain

$$\sin^2 I = \frac{p^2 - \mu^2}{p^2 - 1} \qquad (6)$$

Using this equation Pernter makes out a table of values of $I$ for water, and the corresponding values of $R$ and $D$, for the first fifteen successive internal reflections. A similar table is then made for glass, and the results are subject to comparison.

### FOURTH APPROXIMATION.

Up to this point, as has just been shown, geometrical optics without calculus is sufficient for the study of the rainbow, and this is usually the limit of the treatment applied.

Let us consider some of the rays that penetrate a raindrop at angles of incidence differing considerably from that corresponding to minimum deviation. Without sensible error we may assume 60° for the angle of incidence of the "effective rays". For comparison two other angles of incidence, 50° and 70°, may be selected, each differing 10° from 60°, and we may assume $\mu = 1.333$, corresponding approximately to orange red, or the Fraunhofer line $C$. We will also assume but a single internal reflection for this monochromatic light. Let $SA$ be the ray incident at 60° (fig. 3, Plate II), $S'A'$ at 50°, and $S''A''$ at 70°. Although these incident rays are parallel, the corresponding emergent rays are readily found by equation 2 to be not parallel. For the emergent ray $CE$ the angle of deviation, $D$, is 137° 54′; for $C'E'$, 139° 44′; for $C''E''$, 140° 46′. The emergent wave front is perpendicular to each of these rays. On leaving the drop $CE$ and $C'E'$ diverge, as if they had come from some point, $F$, while $CE$ and $C''E''$ converge, crossing at the point $G$. If $P$ be a point on the least deviated ray, $CE$, about which the effective rays are most crowded, the wave front $PR$ on the upper side of $PE$ will be convex, while the part $PQ$ on the lower side will be concave, toward the direction of propagation. This curvature indicates the development of phase difference on emergence, so that the mutual relation of the different components of the beam is like that of rays issuing from a diffraction grating. Interference bands of alternate brightness and darkness are hence superposed on the main sheaf of effective rays and may become plainly noticeable along its margins.

The rainbow is thus a complex result of both refraction and interference of light. We have assumed the incident rays to be parallel. But this is not strictly true. Each illuminated point on a drop of water in mid-air receives light from the whole disk of the sun, which is more than half a degree in angular diameter. The incident sheaf is hence conical. A variety of overlapping spectra are thus produced by refraction, widening the rainbow beyond the requirements of the ordinary theory, and greatly diminishing the purity of the colors observed. The extent of these disturbances depends much on the clearness or haziness of the atmosphere. In any case the illumination of the air in the direction of the sun produces an effective area with a diameter several times as great as that of the solar disk; and if this area is much charged with vapor the rainbow colors become so mixed that scarcely more than a whitish arch is distinguishable. The same disturbing influences destroy the sharpness of the interference bands just discussed. No theory of the rainbow can therefore be made to fit exactly the phenomena as ordinarily observed because we can not quite realize the assumptions implied; but under favorable circumstances the interference bands have been repeatedly traced, particularly along the inner margin of the primary bow at its upper part. They are known as supernumerary bows.

The complete theory of the rainbow thus requires a mathematical investigation of the curved wave front of the emergent rays. This was first done about 1835 by Potter. It requires also a determination of the intensity at any point receiving the light thus subjected to interference. This was done by Airy in 1836. The process is complex and leads to an integral, the values of which were calculated by Airy for a variety of wave lengths by successive approximation. No one but a skilled mathematician could be expected to understand or repeat the details of the work.

From the theory of diffraction it may be shown that the width and the degree of separation of the interference bands is increased with diminishing size of the raindrops. This may be experimentally tested with the spectrometer by the use of small cylinders of glass as media. In Pernter's discussion he describes experiments of this kind, and reaches the conclusion that the rainbows of richest color are those from water drops varying in diameter from about two-tenths to four-tenths of a millimeter. He gives an elaborate trigonometric investigation, which he ascribes to Wirtinger (Innsbruck, 1897), and by which the results of Potter and Airy are attained; but it can not be called elementary, though he claims to have greatly simplified Wirtinger's work. It covers more than six pages of rather fine print, and the majority of readers, if they have any knowledge of Potter and Airy, would perhaps be ready to admit the correctness of the results without plowing through the intricate underbrush of equations. Calculus is indeed avoided, but not with great saving of labor.

Pernter closes his discussion with an earnest appeal to all teachers in secondary schools to give in full the correct theory of the rainbow. He regards it "an irrefusable duty" (eine unabweisliche Pflicht). All of the observed phenomena he considers as postulates of the correct theory and in contradiction to the Descartes theory of "effective rays," which he thinks should give place to that of "effective wave surfaces". He proclaims as his aim that no one henceforward should teach a false theory of the rainbow, since the means are now at hand for giving the correct theory in a way easily intelligible to school pupils (den Schülern leicht verständlichen Weise). How easy this may be, it would hardly be wise to accept on trust from one who is plainly an enthusiast. Probably the majority of physicists will continue to believe that the colors of the rainbow are due chiefly to refractive dispersion. This may be true without any disregard of the masterly work of Airy or any faulty observation of the phenomena of interference.

## RECENT PAPERS BEARING ON METEOROLOGY.

H. H. KIMBALL, Librarian.

The subjoined titles have been selected from the contents of the periodicals and serials recently received in the Library of the Weather Bureau. The titles selected are of papers or other communications bearing on meteorology or cognate branches of science. This is not a complete index of the meteorological contents of all the journals from which it has been compiled; it shows only the articles that appear to the compiler likely to be of particular interest in connection with the work of the Weather Bureau. Unsigned articles are indicated by a ——.

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